

CAN DRY MERGING EXPLAIN THE SIZE EVOLUTION OF EARLY-TYPE GALAXIES?

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ABSTRACT

The characteristic size of early-type galaxies (ETGs) of given stellar mass is observed to increase significantly with cosmic time, from redshift $z \gtrsim 2$ to the present. A popular explanation for this size evolution is that ETGs grow through dissipationless (“dry”) mergers, thus becoming less compact. Combining N-body simulations with up-to-date scaling relations of local ETGs, we show that such an explanation is problematic, because dry mergers do not decrease the galaxy stellar-mass surface-density enough to explain the observed size evolution, and also introduce substantial scatter in the scaling relations. Based on our set of simulations, we estimate that major and minor dry mergers increase half-light radius and projected velocity dispersion with stellar mass as $R_e \propto M_*^{1.09 \pm 0.29}$ and $\sigma_{e2} \propto M_*^{0.07 \pm 0.11}$, respectively. This implies that: 1) if the high- z ETGs are indeed as dense as estimated, they cannot evolve into present-day ETGs via dry mergers; 2) present-day ETGs cannot have assembled more than $\sim 45\%$ of their stellar mass via dry mergers. Alternatively, dry mergers could be reconciled with the observations if there was extreme fine tuning between merger history and galaxy properties, at variance with our assumptions. Full cosmological simulations will be needed to evaluate whether this fine-tuned solution is acceptable.

Subject headings: galaxies: elliptical and lenticular, cD — galaxies: formation — galaxies: kinematics and dynamics — galaxies: structure — galaxies: evolution

1. INTRODUCTION

In the hierarchical model of structure formation, galaxy mergers are expected to play a central role in the assembly and evolution of galaxies. If present-day early-type galaxies (ETGs) have experienced mergers in relatively recent times ($z \lesssim 1 - 2$), most of these mergers must have been dissipationless or “dry”, because the old stellar populations of ETGs (e.g. Thomas et al. 2005) are inconsistent with substantial recent star formation.

Present-day ETGs satisfy several empirical correlations between half-light radius R_e , central stellar velocity dispersion σ_0 , bulge luminosity L , stellar mass M_* , black-hole mass M_{BH} and gravitational lensing mass M_{lens} , such as the L - σ_0 (Faber & Jackson 1976), L - R_e (Kormendy 1977), $M_{\text{BH}}-L$ (Magorrian et al. 1998), $M_{\text{BH}}-\sigma_0$ (Ferrarese & Merritt 2000; Gebhardt et al. 2000), $M_{\text{BH}}-M_*$ (Marconi & Hunt 2003), $M_{\text{lens}}-R_e$ and $M_{\text{lens}}-\sigma_0$ relations (Nipoti, Treu, & Bolton 2009, hereafter NTB09), the Fundamental Plane (hereafter FP, relating L , R_e and σ_0 ; Dressler et al. 1987; Djorgovsky & Davis 1987) and the lensing Mass Plane (relating M_{lens} , σ_0 and R_e ; Bolton et al. 2007, 2008b). The existence of these scaling laws has been used to establish that present-day ETGs did not form by several dry mergers of lower mass progenitors *obeying the same scaling laws*, because as an effect of dry mergers the galaxy size increases rapidly with mass, while the veloc-

ity dispersion remains almost constant, in contrast with the observed correlations (Ciotti & van Albada 2001; Nipoti, Londrillo, & Ciotti 2003; Boylan-Kolchin et al. 2006; Ciotti, Lanzoni & Volonteri 2007, NTB09).

Photometric and spectroscopic observations of high-redshift ($z \gtrsim 1 - 2$) ETGs suggest that these objects may be remarkably more compact than their local counterparts (e.g. Stiavelli et al. 1999; Daddi et al. 2005; Trujillo et al. 2006; Zirm et al. 2007; Cimatti et al. 2008; van der Wel et al. 2008; van Dokkum et al. 2008, hereafter vD08; Saracco, Longhetti, & Andreon 2009). These findings contributed to renew interest in the proposal that dry merging might be a key process in the growth of ETGs, because it is one of the few known mechanisms able to make galaxies less compact (e.g. Khochfar & Silk 2006; Hopkins et al. 2009a; Naab, Johansson, & Ostriker 2009; van der Wel et al. 2009). However, although dry merging works qualitatively in the right direction, it is not clear whether it works quantitatively.

In this Letter we address the question of the viability of dry merging as a process driving the structural evolution of ETGs, by testing whether it is able to produce the local scaling laws with their relatively small intrinsic scatters. For this purpose, we use the set of numerical simulations of dissipationless minor and major mergers presented in NTB09 and test them against the stellar-mass scaling relations of the Sloan Lenses ACS Survey (SLACS) sample of lens ETGs (Auger et al. 2009). This strategy allows us to construct a direct link between the

observed properties of high-redshift ($z \gtrsim 1-2$) galaxies—for which estimates of the stellar masses are available—and realistic simulated galaxies, in which the relative distribution of luminous and dark matter has been calibrated on the lensing-mass scaling relations (NTB09).

Throughout the paper we adopt Salpeter (1955) Initial Mass Function (IMF), which is consistent with the gravitational lensing constraints for SLACS ETGs (Treu et al. 2009b). Observational data are converted to this calibration when necessary. The main results of this paper do not depend on this choice, since they involve stellar-mass ratios and the IMF normalization effectively factors out.

2. OBSERVED STELLAR-MASS SCALING RELATIONS

In the present work we consider the stellar-mass-size, stellar-mass–velocity-dispersion and stellar-mass FP relations derived by Auger et al. (2009) for the SLACS sample of lens ETGs, assuming Salpeter IMF stellar masses and using the velocity dispersions and rest-frame V-band half-light radii derived from Sloan Digital Sky Survey (SDSS) spectroscopy and Hubble Space Telescope photometry. The correlations are obtained using galaxies with stellar masses generally in the range $11 \lesssim \log M_*/M_\odot \lesssim 12$.

The stellar-mass–size relationship is given by

$$\begin{aligned} \log\left(\frac{R_e}{\text{kpc}}\right) &= (0.730 \pm 0.047) \\ &\times \log\left(\frac{M_*}{10^{11}M_\odot}\right) + 0.391 \pm 0.029, \end{aligned} \quad (1)$$

with intrinsic scatter in $\log R_e$ at fixed mass 0.071. The stellar-mass–velocity-dispersion relation is

$$\begin{aligned} \log\left(\frac{\sigma_{e2}}{\text{km s}^{-1}}\right) &= (0.196 \pm 0.033) \\ &\times \log\left(\frac{M_*}{10^{11}M_\odot}\right) + 2.281 \pm 0.021, \end{aligned} \quad (2)$$

where σ_{e2} is the projected velocity dispersion within an aperture radius $R_e/2$. This has an intrinsic scatter in $\log \sigma_{e2}$ at fixed mass of 0.055. Finally we consider the FP-like correlation

$$\begin{aligned} \log c_* &= (0.099 \pm 0.067) \\ &\times \log\left(\frac{M_*}{10^{11}M_\odot}\right) - 0.959 \pm 0.042, \end{aligned} \quad (3)$$

where $c_* \equiv \sigma_{e2}^2 R_e / 2GM_*$ is a dimensionless structure parameter. The intrinsic scatter in $\log c_*$ at fixed M_* is 0.077.

We recall that SLACS lenses are indistinguishable from control samples of SDSS galaxies with the same stellar velocity dispersion and size, in terms of luminosity and distribution of environments (Bolton et al. 2006; Treu et al. 2006; Bolton et al. 2008a; Treu et al. 2009a). In addition, as discussed in Auger et al. (2009), the above scaling relations are consistent with other scaling relations derived for larger samples of SDSS galaxies with a similar range of masses (e.g. Hyde & Bernardi 2009): in particular the intrinsic scatter of the M_* - R_e relation is consistent with the observed scatter of the widely used correlation found by Shen et al. (2003).

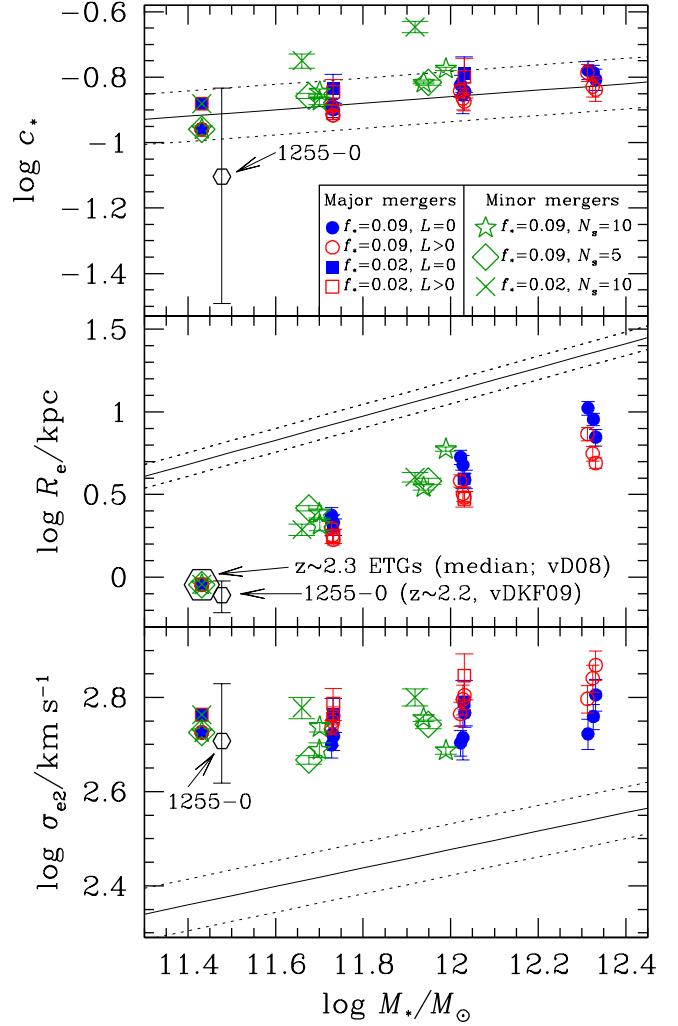


FIG. 1.— Structural parameter $c_* \equiv \sigma_{e2}^2 R_e / 2GM_*$ (top panel), effective radius (central panel) and projected velocity dispersion (bottom panel) as functions of the stellar mass. The solid and dashed lines represent the local observed correlations (equations 1–3), with the associated intrinsic scatters. The big hexagon represents the median M_* and R_e for a sample of nine $z \sim 2.3$ ETGs (vD08). The small hexagons with error bars represent the ETG 1255-0 ($z = 2.186$; vDKF09). The other points and error bars represent the average values and the $1-\sigma$ scatters (due to projection effects) for the simulated galaxies of the merger hierarchies indicated in the top panel (f_* is the stellar mass fraction, L is the orbital angular momentum modulus and N_s is the number of satellites per step).

3. EFFECT OF DRY MERGERS ON COMPACT HIGH- z EARLY-TYPE GALAXIES

Here we combine the scaling laws described above, observations of high- z ETGs and the results of the N-body simulations presented in NTB09 to address the question of whether dry mergers can be responsible for the observed size evolution of ETGs. The set of simulations (see NTB09 for details) consists of both major and minor dry-merger hierarchies, i.e. sequences of two or three steps in each of which the galaxy mass increases by a factor of ~ 2 as a consequence of either a binary equal-mass merger or the accretion of N_s smaller satellites. The seed galaxies and the satellites are spherical, with Navarro, Frenk & White (1996) dark-matter distri-

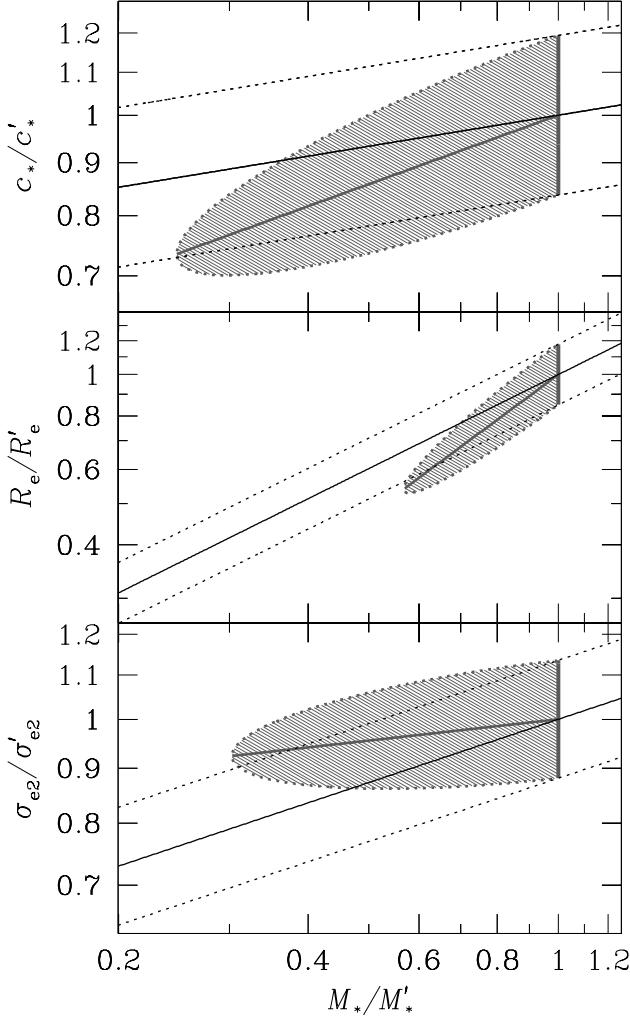


FIG. 2.— The shaded areas represent the distributions in the M_* - c_* , M_* - R_e and M_* - σ_{e2} planes of allowed dry-merging progenitors of local ETGs with stellar mass M'_* (vertical bars). The upper and lower boundaries of the shaded areas correspond to $1-\sigma$ of the distributions, while the solid lines within the shaded areas show their average values. c'_* , R'_e and σ'_{e2} are the average values of c_* , R_e , and σ_{e2} for local ETGs with mass M'_* . The local observed correlations are plotted as in Fig. 1.

bution, Dehnen (1993) stellar distribution (with central logarithmic slope $\gamma = 1.5$), and no gas. Altogether we consider eight major-merger hierarchies (differing in the orbital energy and angular momentum of the galaxy encounters, and in the stellar mass fraction f_* of the seed galaxies) and four minor-merger hierarchies (differing in f_* , N_s and in the phase-space distribution of the satellites’ centers of mass). Each galaxy collision is followed up to the virialization of the merger remnant. In the second and third steps of the hierarchies the remnants of the previous steps are used to realize the initial conditions.

The seed galaxies (and consequently all the end-products of each merging hierarchy) can be rescaled by fixing arbitrarily the simulation mass and length scales \tilde{M}_* and \tilde{r}_* (see NTB09). Though the relative effect of dry mergers on the galaxy structure and kinematics is independent of \tilde{M}_* and \tilde{r}_* , it is useful to fix these quantities, without loss of generality, to make the comparison

with observations straightforward. For our purpose, it is natural to consider seed galaxies with stellar masses and sizes similar to those of high- z ETGs. Here we take as reference the sample of nine $z \sim 2.3$ ETGs studied by vD08, having median stellar mass $\langle M_* \rangle \simeq 2.7 \times 10^{11} M_\odot$ (assuming Salpeter IMF; Kriek et al. 2008) and median effective radius $\langle R_e \rangle = 0.9$ kpc. These galaxies have a factor of ~ 5 smaller size than local ETGs of similar mass, as apparent from the central panel of Fig. 1, where their median location in the M_* - R_e plane can be compared with the stellar-mass-size correlation (1) observed locally.

We then fix \tilde{M}_* and \tilde{r}_* such that all our seed galaxy models have total stellar mass $M_* = 2.7 \times 10^{11} M_\odot$ and $R_e = 0.9$ kpc (symbols inside the big hexagon in Fig. 1). As a consequence, the velocity unit is given, so our seed galaxy models have projected velocity dispersions $\sigma_{e2} = 532 \text{ km s}^{-1}$ ($f_* = 0.09$) and $\sigma_{e2} = 579 \text{ km s}^{-1}$ ($f_* = 0.02$). In the M_* - σ_{e2} plane (bottom panel of Fig. 1) these models (represented by the left-most symbols in the diagram) lie well above the local observed correlation (2). We have little information on the velocity dispersion of high- z ETGs (see Cenarro & Trujillo 2009; Cappellari et al. 2009; van Dokkum, Kriek, & Franx 2009, hereafter vDKF09): for 1255-0, an ETG at $z = 2.186$ with stellar mass $M_* \simeq 3 \times 10^{11} M_\odot$ (after conversion to Salpeter IMF) and half-light radius $R_e = 0.78 \pm 0.17$ kpc (Kriek et al. 2009), vDKF09 tentatively measured projected velocity dispersion $510^{+165}_{-95} \text{ km s}^{-1}$, consistent within the uncertainties with σ_{e2} of our seed galaxy models (see Fig. 1, bottom panel). Given the uncertainties on σ_{e2} , also the structural parameter c_* is poorly constrained for high- z ETGs. Our seed-galaxy models—which were constructed to lie exactly on the lensing Mass Plane (NTB09)—have $c_* = 0.11$ for $f_* = 0.09$ and $c_* = 0.13$ for $f_* = 0.02$ (left-most symbols in the top panel of Fig. 1), consistent, for $M_* \sim 3 \times 10^{11} M_\odot$, with the correlation (3) found for SLACS galaxies, and also with the highly uncertain value of c_* estimated for the high- z ETG 1255-0.

In Fig. 1 the points with $\log M_*/M_\odot > 11.6$ show the location of the merger remnants of all steps of the hierarchies in the M_* - c_* , M_* - R_e and M_* - σ_{e2} planes. For the adopted values of the length and mass scales, the timescale to complete one step of the merging hierarchies is in the range 0.5 – 1.7 Gyr, so all hierarchies can be comfortably completed in the ~ 10 Gyr elapsing from $z \sim 2$ to the present. The location of the merger remnants with respect to the local scaling laws is quite dependent on the details of their merging history, but it is apparent that all the merger remnants lie significantly below the M_* – R_e relation and above the M_* – σ_{e2} relation. On average, minor mergers increase more the galaxy size than major mergers, consistent with the results of Naab, Johansson, & Ostriker (2009), but we also find that different minor-merging events produce remnants with significantly different R_e and σ_{e2} for similar M_* , even when the initial conditions differ just by the relative phase-space distribution of the centres of mass of the satellites and the central galaxy (see the right-most pairs of stars in Fig. 1).

The behavior of our minor-merger hierarchies in the M_* - σ_{e2} plane deserves some discussion. When a galaxy

grows by accreting satellites on almost parabolic orbits (as is the case for our minor-merger steps; see NTB09), the virial velocity dispersion of the remnant is lower than that of the progenitor *if the mass loss is negligible* (Bezanson et al. 2009; Naab, Johansson, & Ostriker 2009). The fact that in some of our minor-merger steps the remnant has slightly higher projected (and virial) velocity dispersion than the progenitor must be ascribed to the significant loss of luminous (see Fig. 1) and dark (see NTB09) matter, which is known to have the effect of increasing the velocity dispersion (see Nipoti, Londrillo, & Ciotti 2003).

In general the merger remnants lie close to the FP-like relation M_*-c_* , consistent with previous studies considering the FP (González-García & van Albada 2003; Nipoti, Londrillo, & Ciotti 2003; Boylan-Kolchin et al. 2006) or the lensing Mass Plane (NTB09). An exception is the minor-merging hierarchy with $f_* = 0.02$ seed galaxy (crosses in the diagrams), in which c_* increases significantly with stellar mass, reflecting the relatively low M_* and high σ_{e2} due to substantial mass loss.

Altogether, considering both major and minor merger hierarchies, our results confirm that dry mergers bring compact ETGs closer to the observed correlations. However, quantitatively, the process is not efficient enough to explain the observed size evolution. We note that the final merger remnants (the end-products of the last steps of the hierarchies) have exceptionally high stellar masses ($M_* \gtrsim 10^{12} M_\odot$), so one cannot invoke more growth via dry mergers to obtain systems with surface mass density as low as observed in local galaxies. Furthermore, velocity dispersion is approximately conserved along the merger hierarchies, and objects with $\sigma_{e2} \sim 500 \text{ km s}^{-1}$ are not observed in the local universe.

4. CONSTRAINTS ON THE STELLAR-MASS ASSEMBLY HISTORY OF PRESENT-DAY EARLY-TYPE GALAXIES

Taken at face value, the stellar masses and sizes of the high- z ETGs mean that these systems cannot evolve into present-day ETGs via dry mergers. However, possible observational biases in the high- z measurements (for instance, that the sizes are underestimated; Hopkins et al. 2009b) could make the discrepancy between high and low redshift systems smaller. Thus, if one only considers *average* properties, dry mergers may perhaps be still considered a viable evolutionary mechanism. However, recovering the average size of local ETGs is not sufficient: additional constraints come from the small *intrinsic scatter* of observed stellar-mass scaling relations, which constrains the dry-merger mass assembly history of present-day ETGs, *independently of the actual compactness of their high- z counterparts*. A first attempt of constraining the merging history of ETGs using the scatter in the stellar-mass-size relation was performed by Shen et al. (2003), who—on the basis of an analytic parametrization of the size growth due to dry mergers—found that a certain degree of fine tuning in the orbital parameters of the galaxy encounters is required in order to reproduce the local M_*-R_e relation of their SDSS sample of ETGs. We take here a step further, by taking advantage of N-body merger simulations and up-to-date stellar-mass scaling laws, including information on stellar velocity dispersion.

We quantify the growth of galaxies by dry merging by

approximating the dependence of the structural parameters on stellar mass with power-law functions (see NTB09 for the lensing-mass analogs): $R_e \propto M_*^{\beta_R}$, $\sigma_{e2} \propto M_*^{\beta_\sigma}$ and $c_* \propto M_*^{\beta_c}$. To each step of a hierarchy we associate a value of β_R by calculating $\beta_R \equiv \Delta \log R_e / \Delta \log M_*$, where Δ indicates variation between the remnant and the progenitor. The resulting 30 values of β_R are distributed with average $\langle \beta_R \rangle = 1.09$ and standard deviation $\delta \beta_R = 0.29$. Doing the same for β_σ and β_c , we get $\langle \beta_\sigma \rangle = 0.07$, $\delta \beta_\sigma = 0.11$ and $\langle \beta_c \rangle = 0.22$, $\delta \beta_c = 0.13$. Assuming that the galaxy merging history is characterized by slopes β normally distributed with these averages and standard deviations, we can use these quantities to describe how dry mergers move galaxies in the planes M_*-c_* , M_*-R_e and $M_*-\sigma_{e2}$: the relatively large values of $\delta \beta / \beta$ we find mean that dry mergers introduce substantial scatter in these planes.

For the dry-merging scenario to be viable it must not introduce in the scaling relations more scatter than observed. We can use this condition to constrain the properties of the candidate progenitors of local ETGs, assuming as working hypothesis that they formed by dry merging. Let us consider, for example, local ETGs with given stellar mass M'_* in the range $10^{11} - 10^{12} M_\odot$ probed by the SLACS sample: in Fig. 2 the distributions (within $1-\sigma$) of c_* , R_e and σ_{e2} for these galaxies are represented by the vertical bars, while the loci in the M_*-c_* , M_*-R_e and $M_*-\sigma_{e2}$ planes of their allowed dry-merging progenitors are shown by the shaded areas. Galaxies lying out of these areas, growing by major or minor dry merging, would populate regions of the parameter space inconsistent with the local observed distributions at the reference mass M'_* . It is apparent that the strongest constraint comes from the M_*-R_e plane (central panel), where the allowed region for progenitors spans ~ 0.26 dex in M_* . This means that a growth in stellar mass by dry merging by more than a factor of ~ 1.8 (and in size by more than a factor of ~ 1.9) is excluded on the basis of our set of simulations. In other words, present-day massive ($M_* \sim 10^{11} - 10^{12} M_\odot$) ETGs cannot have assembled, on average, more than $\sim 45\%$ of their stellar mass through dry merging. Quantitatively, the constraints on the mass assembly history depend on the specific choice of the orbital parameters and mass ratios of the galaxies: in our set of merging hierarchy simulations there are more major than minor mergers, and we explore a wide range of orbital parameters. One might get different numbers by considering more minor-merging simulations or excluding parts of the orbital parameter space. For instance, if we consider only the 8 minor merger steps, we get $\langle \beta_R \rangle = 1.30$ and $\delta \beta_R = 0.40$, which gives an upper limit of $\sim 35\%$ to the fraction of stellar mass assembled via dry mergers by local ETGs. In any case, it is clear that *a remarkable degree of fine tuning is required to reproduce the tightness of the local scaling relations with dry mergers*.

5. CONCLUSIONS

Dry merging makes galaxies less compact. For this reason it has been proposed to be the key to reconcile the compactness of high- z ETGs with the lower stellar-mass surface-density of local ETGs.

Our quantitative analysis based on N-body simulations

shows that *it is very hard to reproduce with dry mergers the growth in size of a factor of ~ 5 between $z \gtrsim 2$ and today reported in the literature for $M_* \sim 10^{11} M_\odot$ ETGs*, because the average size growth produced by dry merging is not sufficient. The tightness of the local scaling laws of ETGs provides an additional and stringent constraint for the dry-merging scenario. As we have shown, generic dry mergers tend to increase the scatter rather than decrease it because they cannot preserve simultaneously the correlations between stellar mass, velocity dispersion and effective radius. On the basis of our set of major and minor merging simulations, we conclude that—*independent of the actual compactness of higher- z ETGs—typical present-day massive ETGs did not assemble more than $\sim 45\%$ of their stellar mass and grew more than a factor ~ 1.9 in size via dry merging.* A similar upper limit is found also for the total (dark plus luminous) mass assembly on the basis of the lensing-mass scaling laws (NTB09).

Is this then the end of dry mergers as a major evolutionary mechanism? The only way out could be provided by a high degree of fine tuning of the mix of progenitors and orbits. Although not a natural scenario in our opinion, this fine tuning could perhaps reproduce such tight

scaling relations and thus save the day. A systematic exploration of cosmologically motivated merging hierarchies is necessary to find out whether such an extreme fine tuning actually occurs.

The question of what drives the apparent size evolution of ETGs remains open. A possibility is that a combination of different astrophysical processes and observational biases can do the job (e.g. Hopkins et al. 2009c), but it is not excluded that the answer is to be found exploring more exotic scenarios, such as those assuming non-standard dark matter (Lee 2008; Ferrer, Nipoti, & Ettori 2009).

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